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Grain quality characteristics of spring wheat (*Triticum aestivum*) as affected by free-air CO_2 enrichment

P. Högy[a,*], M. Brunnbauer[b], P. Koehler[b], K. Schwadorf[c], J. Breuer[c], J. Franzaring[a], D. Zhunusbayeva[a], A. Fangmeier[a]

[a] *Universität Hohenheim, Institute for Landscape and Plant Ecology, Oekologiezentrum 2, August-von-Hartmann Str. 3, D-70599 Stuttgart, Germany*
[b] *German Research Centre for Food Chemistry and Hans-Dieter-Belitz-Institute for Cereal Research, Lise-Meitner-Straße 34, D-85354 Freising, Germany*
[c] *Universität Hohenheim, Landesanstalt für Landwirtschaftliche Chemie, Emil-Wolff-Strasse 14, D-70599 Stuttgart, Germany*

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ABSTRACT

Spring wheat (*Triticum aestivum* L. cv. Triso) was grown in a free-air carbon dioxide (CO_2) enrichment (FACE) system at Stuttgart–Hohenheim (Germany) in 2008 to examine effects on crop yield and grain quality. Elevated CO_2 had no significant impacts on aboveground biomass and grain yield components except for an increase in thousand grain weight by 5.4% with size distribution shifted towards larger grains. Total grain protein concentration decreased by 7.9% under CO_2 enrichment, and protein composition was altered. Total gliadins and their single types (ω5-gliadins, ω1,2-gliadins, α-gliadins, and γ-gliadins) were reduced, while albumins/globulins, total glutenins and their subunits were not influenced. The gluten proteins (gliadins plus glutenins) were lowered by 11.3% in the high-CO_2 treatment, whereas proportions of gluten protein types were slightly affected as only ω1,2-gliadins decreased. Accordingly, all proteinogenic amino acids were decreased by 4.2 to 7.9% in concentrations per unit flour mass, although partly below the level of statistical significance. In contrast, the composition of amino acids on a per protein basis remained unaffected except for a decline in serine. Among the minerals, the concentrations of calcium, magnesium, iron and cobalt decreased, while an increase was observed for boron. The concentrations of total non-structural carbohydrates and starch decreased, whereas fructose, raffinose and fructan increased. Total lipid concentration remained unaffected by the CO_2 enrichment, whereas the grain carbon/nitrogen relation was increased by 8.5%. Implications may occur for consumer nutrition and health, and for industrial processing, thus breeding of new wheat cultivars that exploit CO_2 fertilisation and maintain grain quality properties is regarded as one potential option to assure the supply chain for the future.

1. Introduction

A major challenge for the agricultural production is to feed the world population which is expected to grow from 6.8 billion today to 9.1 billion by 2050. There is thus a need to sustain agricultural systems that produce more food, while simultaneously adapting to a changing climate. The major driver of climate change is the rapid increase in atmospheric carbon dioxide (CO_2)[1] concentration due to anthropogenic activities, which is predicted to have increased from pre-industrial 280 $\mu L\,L^{-1}$ to 550 $\mu L\,L^{-1}$ by the middle of this century (Meehl et al., 2007). Besides the indirect impacts via rise in global surface temperature and changes in precipitation patterns, elevated CO_2 will directly affect both productivity of agricultural plants and crop quality.

Wheat is one of the world's major food crops in temperate regions and mature grains are used as flour for the production of bread and other products. In 2008, the worldwide production

* Corresponding author at: Universität Hohenheim (320), Institute for Landscape and Plant Ecology, Oekologiezentrum 2, August von Hartmann Str. 3, D-70599 Stuttgart, Germany. Tel.: +49 711 459 23819; fax: +49 711 459 23044.
E-mail addresses: petra.hoegy@uni-hohenheim.de (P. Högy), Markus.Brunnbauer@lrz.tu-muenchen.de (M. Brunnbauer), peter.koehler@tum.de (P. Koehler), schwadorf@lachemie.uni-hohenheim.de (K. Schwadorf), breuer@lachemie.uni-hohenheim.de (J. Breuer), juergen.franzaring@uni-hohenheim.de (J. Franzaring), dinaz@uni-hohenheim.de (D. Zhunusbayeva), andreas.fangmeier@uni-hohenheim.de (A. Fangmeier).

[1] **Abbreviations**: AMB = ambient CO_2 concentration, ANOVA = analysis of variance, Asx = asparagine/aspartic acid, C_3 = metabolic pathway for carbon fixation in photosynthesis, CO_2 = carbon dioxide, DW = dry weight, EC = growth stage, ELE = elevated CO_2 concentration, FACE = free-air CO_2 enrichment, Glx = glutamine/glutamic acid, HMW = high molecular weight, LMW = low molecular weight, NSC = non-structural carbohydrates, ns = no significance, *P* = level of probability, and TGW = thousand grain weight.

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of wheat was 683 million metric tons (FAOSTAT, 2011). Earlier single and multiple-year free-air CO_2 enrichment (FACE) experiments have demonstrated that in C_3 species such as wheat high atmospheric CO_2 acts as "carbon (C) fertiliser" and increases total aboveground biomass production by an average of 11.8% and 8.4%, respectively (Kimball et al., 1995; Högy et al., 2009a), when supplied with ample nutrients and water. While data on the individual yield parameters are sometimes conflicting (Kimball et al., 2001; Li et al., 2001; Manderscheid et al., 2004; Högy et al., 2009a,b), CO_2 enrichment to 550–600 $\mu L\,L^{-1}$ is well established to increase grain yield by 10–16% (Kimball et al., 2001; Kimball, 2006; Long et al., 2006; Högy et al., 2009a). However, the extent of the CO_2 response on grain yield may vary among crop cultivars and according to environmental conditions (Kimball et al., 2002; Ainsworth and Long, 2004).

Only few papers dealing with CO_2-induced impacts on chemical grain quality parameters of interest for different markets and utilisation requirements have been published and among these there are often contradictory findings (e.g. reviews by Idso and Idso, 2001; Kimball et al., 2002; Högy and Fangmeier, 2008; Bender and Weigel, 2010; DaMatta et al., 2010; Moretti et al., 2010; Uprety et al., 2010). Previous experiments under field conditions demonstrated that several grain quality traits are not affected by elevated CO_2 whereas other authors found evidence for serious impacts. The latter studies reported that especially compounds containing nitrogen (N) were decreased in grains under CO_2 enrichment (Wieser et al., 2008; Högy et al., 2009a, 2010), with both beneficial and adverse consequences for nutritional dietary value and processing quality. Although there is a well-known negative correlation between grain yield and N concentration (Sinclair, 1998; Barneix, 2007), CO_2 enrichment additionally improves resource use efficiency in terms of water and N and changes the chemical composition of vegetative plant parts (Cotrufo et al., 1998; Jablonski et al., 2002; Loladze, 2002). As grain filling is largely dependent on the remobilisation and supply of assimilates such as sucrose and amino acids and their metabolic regulation, grain storage metabolism and thus key quality traits will be changed under elevated CO_2 concentrations, too.

Wheat grains are important sources for carbohydrates, proteins, amino acids, lipids and minerals (Pomeranz, 1987; Shewry, 2009), which determine the nutritional dietary value and important end-use quality characteristics. Especially the concentration of total proteins is an important economic factor as it is a crucial determinant of bread making quality. In previous field studies, the most pronounced finding concerning nutritional quality of a cereal-based diet is a CO_2-induced decrease of total grain protein concentration by 3.5–14.3% (Kimball et al., 2001, 2002; Taub et al., 2008; Wieser et al., 2008; Högy et al., 2009a,b, 2010; Erbs et al., 2010), which is accompanied by a change in protein composition (Wieser et al., 2008; Högy et al., 2009a,b). The latter observation results mainly from a reduction in gluten proteins, either due to an exclusive decline in gliadins and their types (Högy et al., 2009a,b) or in both gliadins and glutenins fractions and types (Wieser et al., 2008), which in turn may affect traits fundamental to producing high-quality bread. Accordingly, an overall decline in proteinogenic amino acid concentrations was reported in a three-year study (Högy et al., 2009a), while significant CO_2 effects were limited to glycine (Gly) and valine (Val), and glutamine/glutamic acid (Glx) as a trend, in a single-year experiment (Högy et al., 2009b). Also the composition of proteinogenic amino acids was changed with either non-essential amino acids being more affected than essential (Högy et al., 2009a) or no clear response pattern of different types (Högy et al., 2009b). Starch is the major C pool in grains, which was either not affected (Högy et al., 2009a; Erbs et al., 2010) or increased (Porteaus et al., 2009) in previous FACE studies. Although non-starch polysaccharides constitute less than 3% of the total flour mass, they are important in the bread making process as a contributor to the distribution of water in dough as well as a supplier for sugar required by yeast (Stone and Savin, 1999). The concentration of fructose and fructan as well as amounts per area of total and individual non-structural carbohydrates (NSC), except for starch, increased in a previous three-year FACE experiment (Högy et al., 2009a).

Also lipids, representing minor components with 1–1.5% of the grain mass, affect baking performance. However, lipids were not affected in concentration but only increased in harvested amount per area under CO_2 enrichment (Högy et al., 2009a). In the same study, minerals such as potassium (K), molybdenum (Mo) and lead (Pb) increased at least as a trend, while magnesium (Mg), iron (Fe), cadmium (Cd) and silicium (Si) decreased, suggesting that elevated CO_2 may affect grain quality in terms of nutritional value and end-product quality. Erbs et al. (2010) reported depletion in sulphur (S) concentration, while individual macro- and micro-elements remained unaffected in a single-year study (Högy et al., 2009b). Despite intensive research activities, there is still a very limited understanding of CO_2-induced impacts on the factors controlling rate and duration of grain development, mineral allocation, protein and amino acid accumulation as well as lipid and carbohydrate synthesis and accumulation in grains. Data from experiments under realistic field conditions are thus important in order to identify the implications for grain quality in terms of market value, consumer nutrition and health, and industrial application properties under elevated CO_2.

Therefore, in the present study, spring wheat was grown as monoculture in a FACE experiment under European field conditions in order to focus on aboveground biomass production, crop yield and a comprehensive number of grain quality traits. It was hypothesised that: (i) elevated CO_2 would affect plant growth and the effects vary between different plant fractions; (ii) grain yield would be increased in the high-CO_2 treatment; (iii) CO_2 enrichment would especially decrease N-rich grain components that are important for nutritional and technological properties; (iv) CO_2-induced responses on grain quality are comparable to previous studies performed at the same site involving lower planting densities.

2. Materials and methods

2.1. Crop management and grain quality analyses

The experiment was carried out in a mini-FACE system at the experimental station Heidfeldhof (9°11′E, 48°42′N, 395 m asl) of the University of Hohenheim, Germany. A local spring wheat cultivar (*Triticum aestivum* L. cv. Triso; quality grade E for excellent baking quality) was grown at field plots without racks (CON), experimental plots under ambient CO_2 with racks (AMB) and elevated CO_2 rings with racks for the supply of the gas (ELE) with five replicates, respectively. In order to apply concentrations expected for the next decades (Meehl et al., 2007), the target CO_2 concentration at canopy level in the ELE treatment was set at ambient plus 150 $\mu L\,L^{-1}$ CO_2. For details on the technical equipment see Erbs and Fangmeier (2006).

Seeds were manually sown (08 April 2008) in rows spaced of 12 cm to reach a final density of 360 plants m^{-2}. Fertiliser was applied to reach a local favourable nutrient level of 130 kg N ha^{-1} (46/15.5/15.5/23) at different growth stages (EC 21, EC 29, EC 32, EC 41-59; Tottman and Broad, 1987). Plots were additionally fertilised with 60 kg phosphorus (P) ha^{-1}, 120 kg K ha^{-1} and 18 kg Mg ha^{-1} at EC 21 using Thomaskali®. In addition, 0.03 kg boron (B) ha^{-1}, 0.45 kg Mg ha^{-1}, 0.36 kg S ha^{-1} and 0.03 kg manganese (Mn) ha^{-1} were applied at EC 32 by using a trace element fertiliser. Weeds were removed manually and plant protection was carried out in